

Cosmological Invisible Decay of Light Sterile Neutrinos

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We introduce a cosmological invisible decay of the sterile neutrino with the eV-scale mass indicated by short-baseline neutrino oscillation experiments in order to allow its full thermalization in the early Universe. We show that the fit of the cosmological data is practically as good as the fit obtained with a stable sterile neutrino without mass constraints, which has been recently considered by several authors for the explanation of the observed suppression of small-scale matter density fluctuations and for a solution of the tension between the Planck and BICEP2 measurements of the tensor-to-scalar ratio of large-scale fluctuations. Moreover, the extra relativistic degree of freedom corresponding to a fully thermalized sterile neutrino is correlated with a larger value of the Hubble constant, which is in agreement with local measurements.

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The recent results of the BICEP2 experiment [1] revived the interest in the cosmological contribution of light sterile neutrinos [2–6]. BICEP2 measured a tensor-to-scalar ratio $r = 0.20^{+0.07}_{-0.05}$ of large-scale fluctuations, which is significantly larger than the upper limits of WMAP [7] ($r < 0.13$ at 95% CL) and Planck [8] ($r < 0.11$ at 95% CL). This tension can be relieved by allowing an extra relativistic particle in the early Universe, which could be a sterile neutrino [2–6]. The effect is due to the correlation between the effective number of relativistic degrees of freedom N_{eff} before photon decoupling (see [9, 10]) and the spectral index n_s of the scalar primordial curvature power spectrum $\mathcal{P}_{\mathcal{R}}(k) = A_s(k/k_0)^{n_s-1}$, with the pivot scale $k_0 = 0.05 \text{ Mpc}^{-1}$, which lies roughly in the middle of the logarithmic range of scales probed by Planck [8]. Keeping fixed the amplitude A_s at $k \sim k_0$, which is constrained by the high-precision Planck data, the scalar contribution to the large-scale temperature fluctuations with $k \ll k_0$ measured by WMAP and Planck can be decreased by an increase¹ of the spectral index n_s . In this way, the WMAP and Planck data leave

more space for the tensor contribution [13] and the corresponding bounds on r are relaxed. However, the increase of n_s induces an increase of small scale fluctuations with $k \gg k_0$, which would spoil the fit of high- ℓ Cosmic Microwave Background (CMB) data if the increase is not compensated by an effect beyond the standard cosmological ΛCDM model. An increase of N_{eff} above the Standard Model value $N_{\text{eff}}^{\text{SM}} = 3.046$ [14] has just the desired effect of decreasing small scale fluctuations (see Ref. [15]). For example, from the fit of CMB data without BICEP2 the authors of Ref. [5] obtained $n_s = 0.970^{+0.011}_{-0.018}$ (1σ) and $\Delta N_{\text{eff}} < 1.18$ (2σ), with $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$, and adding BICEP2 data they found $n_s = 0.986^{+0.016}_{-0.020}$ (1σ) and $\Delta N_{\text{eff}} = 0.82^{+0.40}_{-0.57}$ (1σ).

A fit of cosmological data must take into account also the measurements of the Hubble constant H_0 and of the matter distribution in the Universe. In particular, the measured small-scale matter density fluctuations ($k \sim 0.1 \text{ Mpc}^{-1}$) are smaller than those obtained by evolving the primordial density fluctuations with the relatively large matter density at recombination measured precisely by Planck (see Refs. [16–18]). This discrepancy can be explained by the existence of a massive sterile neutrino with a free-streaming that suppresses the growth of structures which are smaller than the free-streaming length (see, for example, Ref. [10]). A global fit of cosmological data gives a sterile neutrino mass $m_s = 0.44^{+0.11}_{-0.16} \text{ eV}$ (1σ), with $\Delta N_{\text{eff}} = 0.89^{+0.34}_{-0.37}$ (1σ) [5] (see also [3, 4, 6]).

The existence of light massive sterile neutrinos in the early Universe is especially exciting in connection with the indications of short-baseline (SBL) neutrino oscillations found in the LSND experiment [19], in Gallium experiments [20] and in reactor experiments [21–23]. These oscillations can be explained in the 3+1 extension of the standard three-neutrino mixing paradigm with the introduction of a sterile neutrino with a mass $m_s \sim 1 \text{ eV}$ [24, 25], which is significantly larger than the cosmolog-

¹ One could think to alleviate the tension between BICEP2 and WMAP-Planck by decreasing n_s , if the value of r measured by BICEP2 refers to a wavenumber k_1 larger than than the wavenumber $k_2 = 0.002 \text{ Mpc}^{-1}$ corresponding to the WMAP and Planck upper bounds [11, 12]. Since $r_{k_2} \simeq r_{k_1} (k_1/k_2)^{n_s-1-n_t}$, where n_t is the tensor spectral index, for $k_2 < k_1$ and $n_s - 1 - n_t < 0$ we have $r_{k_2} < r_{k_1}$ and the ratio r_{k_2}/r_{k_1} decreases by decreasing n_s . However, one must take into account that WMAP and Planck did not measure directly the tensor fluctuations as BICEP2, but measured the temperature fluctuations, in which the scalar and tensor contributions are indistinguishable. Hence, decreasing n_s increases the scalar contribution to the temperature fluctuations measured by WMAP and Planck at $k_2 < k_1$ and there is less room for a tensor contribution. Therefore the WMAP and Planck upper bounds on r_{k_2} tighten by about the same amount of the decrease of the BICEP2 value of r_{k_2} , maintaining the tension.

ically preferred value mentioned above. In fact, such a large mass would induce an excessive suppression of small-scale matter density fluctuations if the sterile neutrinos are fully thermalized.

The authors of Ref. [5] analyzed the cosmological data, including the BICEP2 results, taking into account the global fit of neutrino oscillation data presented in Ref. [25]. The result of the combined fit shows that a sterile neutrino with a mass at the eV scale is allowed by cosmological data only if it is not fully thermalized in the early Universe: $m_s = 1.19^{+0.15}_{-0.12}$ eV (1σ) and $\Delta N_{\text{eff}} = 0.19^{+0.07}_{-0.15}$ (1σ). The case of a fully thermalized sterile neutrino is disfavored by $\Delta\chi^2 > 10$ [5]. Similar conclusions have been reached before the recent BICEP2 results (see the recent Refs. [18, 26, 27], which take into account the Planck data [8]) and motivated the study of mechanisms which can suppress the thermalization of sterile neutrinos in the early Universe due to active-sterile oscillations before neutrino decoupling [28–31]. Examples are a large lepton asymmetry [31–34], an enhanced background potential due to new interactions in the sterile sector [35–39], a larger cosmic expansion rate at the time of sterile neutrino production [40], and MeV dark matter annihilation [41].

In this letter we propose to solve the tension between the thermalization of the sterile neutrino in the early Universe and the fit of cosmological data with a sterile neutrino having a eV-scale mass by introducing an invisible decay of the sterile neutrino. The decay must be invisible in order not to generate unobserved signals. We assume that the decay products are very light or massless particles belonging to the sterile sector. For example, the eV-scale sterile neutrino ν_s could decay into a lighter sterile neutrino $\nu_{s'}$ and a very light invisible (pseudo)scalar boson² ϕ . The lighter sterile neutrino $\nu_{s'}$ must have very small mixing with the active neutrinos, in order to forbid its thermalization in the early Universe and to preserve the effectiveness of the standard three-neutrino mixing paradigm for the explanation of solar and atmospheric neutrino oscillations. Also the very light invisible boson ϕ has a negligible thermal distribution before the decay, because it belongs to the sterile sector which may have been in equilibrium at very early times, but has decoupled from the thermal plasma at a very high temperature and the densities of all the particles belonging to the sterile sector have been washed out in the following phase transitions and heavy particle-antiparticle annihilations (see, for example, Ref. [44]). Another possible decay which does not need the presence of a light boson is $\nu_s \rightarrow \nu_{s'} \bar{\nu}_{s'} \nu_{s'}$, which needs an effective four-fermion

interaction of sterile neutrinos.

In the invisible decay scenario, the eV-scale sterile neutrino can be fully thermalized in the early Universe through active-sterile oscillations [28–31] and generates the $\Delta N_{\text{eff}} = 1$ indicated by the fit of CMB data with BICEP2. In the first radiation-dominated part of the evolution of the Universe the mass of the sterile neutrino is not important, because it is relativistic. The mass effect is important in the following matter-dominated evolution of the Universe, which leads to the formation of Large Scale Structures (LSS) and the current matter density. The sterile neutrinos which decay into invisible relativistic particles do not contribute to the matter budget. In this way the eV-scale mass of the sterile neutrino indicated by short-baseline oscillation experiments becomes compatible with a full thermalization of the sterile neutrino in the early Universe.

We analyzed the same cosmological data considered in Ref. [5] with a Bayesian analysis performed with the *CosmoMC* Monte Carlo Markov Chain engine [45] modified in order to take into account the invisible decay of the sterile neutrino. For simplicity³, we neglected the energy dependence of the sterile neutrino lifetime and we considered a sterile neutrino with a Fermi-Dirac distribution multiplied by

$$N_s(t) = \Delta N_{\text{eff}} e^{-t/\tau_s}, \quad (1)$$

where t is the cosmic time and τ_s is the effective lifetime of the sterile neutrino. For simplicity, we neglect the energy distributions of the very light or massless invisible decay products (which depend on the specific decay model) and we parameterize their effect with an effective increase of the amount of radiation by $\Delta N_{\text{eff}} (1 - e^{-t/\tau_s})$. Following Refs. [5, 18, 26], we take into account the SBL constraint on m_s through a prior given by the posterior of the global analysis of SBL oscillation data presented in Ref. [25].

Figure 1 shows the 1σ and 2σ marginalized allowed regions in the planes m_s – ΔN_{eff} and H_0 – ΔN_{eff} obtained by fitting the CMB data (Planck+WP+high- ℓ +BICEP2(9bins); see Ref. [5]) with the SBL prior in a model with free ΔN_{eff} and a massive sterile neutrino which decays invisibly. The corresponding numerical values of the cosmological parameters are listed in Tab. I. From the values of $\Delta\chi^2(\text{A})$ and $\Delta\chi^2(\text{B})$ one can see that the fit of cosmological data is even slightly better than that obtained with a stable sterile neutrino without mass constraints (A) and much better than that obtained with a stable sterile neutrino with the SBL mass prior (B).

² The new invisible light (pseudo)scalar boson is assumed to interact only with the sterile neutrinos, without the interactions with the active neutrinos studied in Refs. [42, 43] and references therein.

³ A precise calculation requires the solution of the coupled Boltzmann equations describing the evolution of the distributions of the sterile neutrino and the decay products. The results of such a calculation in the framework of a specific decay model will be presented elsewhere.

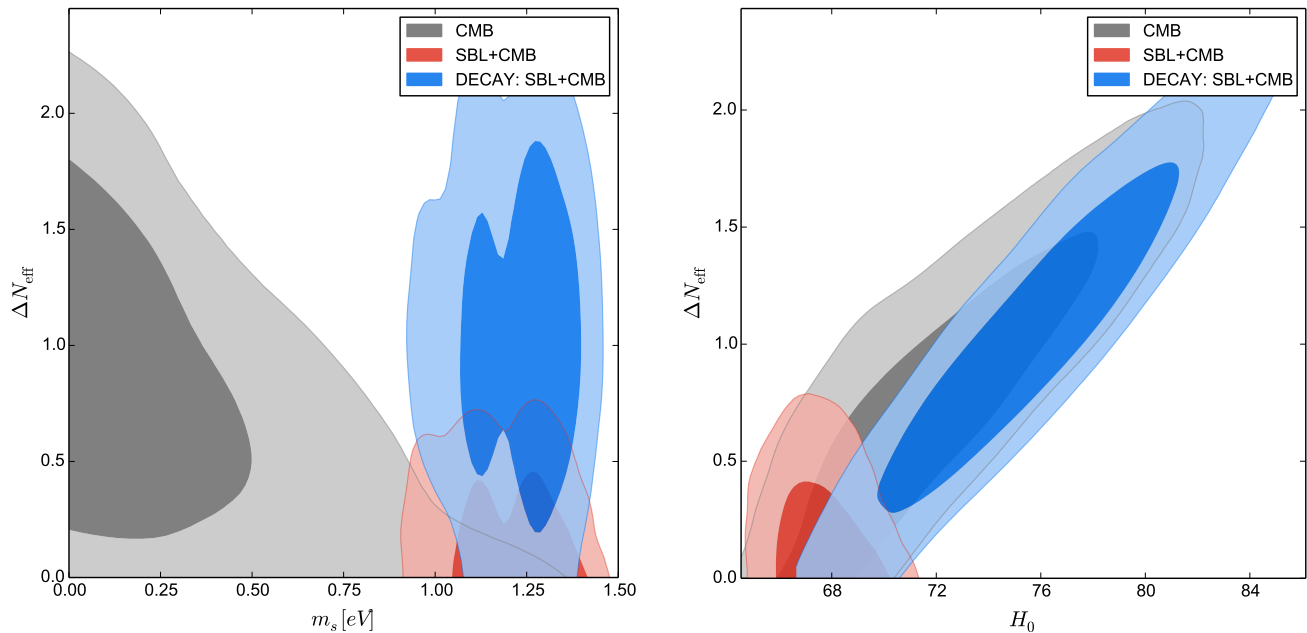


FIG. 1. 1σ and 2σ marginalized allowed regions obtained with CMB data (Planck+WP+high- ℓ +BICEP2(9bins); see Ref. [5]). The gray and red regions are those obtained in Ref. [5] without and with the SBL prior. The blue regions are obtained by adding the invisible sterile neutrino decays.

In Fig. 1 we compared the allowed regions obtained with the invisible decay of the sterile neutrino with the corresponding regions obtained in Ref. [5] for a stable sterile neutrino without and with the SBL prior. One can see that the invisible decay of the sterile neutrino allows $\Delta N_{\text{eff}} = 1$, which corresponds to the full initial thermalization of the sterile neutrino, even if the SBL prior forces the sterile neutrino mass to assume values around 1.2 eV. In practice, the invisible decay of the sterile neutrino allows us to relax the upper bound of about 0.6 for ΔN_{eff} obtained in Ref. [5] with the SBL prior and bring the allowed range of ΔN_{eff} at a level which is similar to that obtained in Ref. [5] without the SBL prior (see also [2–4, 6]). This can also be seen in the upper panel of Fig. 2, which shows the marginalized allowed interval of ΔN_{eff} .

Figure 1 shows also that by allowing the sterile neutrino to decay one can recover a correlation between ΔN_{eff} and H_0 which is similar to that obtained in the analysis of CMB data without the SBL prior. Hence, we obtain that large values of ΔN_{eff} are correlated to large values of the Hubble constant H_0 , which are in agreement with the local measurements of H_0 (see [8, 18]).

From Tab. I one can see that small values of τ_s are preferred, but the uncertainty is very large, because there is no bound at 2σ . The preference for small values of τ_s reflects the bound on a stable sterile neutrino mass given by CMB data (see the grey region in Fig. 1): the bound can be evaded allowing $m_s \sim 1$ eV if the sterile

neutrino decays quickly. However, the uncertainty for τ_s is very large, because of the wide range of allowed values of ΔN_{eff} . Hence, we performed also a run of CosmoMC with $\Delta N_{\text{eff}} = 1$, which gave the more stringent upper bounds $\tau_s < 0.11 T_0$ (1σ), $0.26 T_0$ (2σ), where T_0 is the age of the Universe.

Figure 3 shows the 1σ and 2σ marginalized allowed regions corresponding to those of Fig. 1 and obtained by adding the same cosmological data considered in Ref. [5] on Large Scale Structures (LSS), local H_0 measurements, cosmic shear (CFHTLenS) and the Sunayev-Zeldovich effect cluster counts from Planck (PSZ). One can see that also this wide data set allows $\Delta N_{\text{eff}} = 1$ and the allowed range of ΔN_{eff} is similar to that obtained without the SBL prior (see also Fig. 2). As in Fig. 1, ΔN_{eff} and H_0 are approximately correlated, indicating relatively large values of H_0 for $\Delta N_{\text{eff}} = 1$, which are in agreement with the local measurements of H_0 .

The $\Delta\chi^2$ values in Tab. I show that the fit of the cosmological data is excellent. From Tab. I one can also see that the sterile neutrino lifetime τ_s has a 1σ lower bound, without a 2σ bound. In this case, large values of τ_s are preferred because the free-streaming of a massive sterile neutrino can explain the observed suppression of small-scale matter density fluctuations [3–6, 16–18]. The large uncertainty on τ_s is again due to the wide range of allowed values of ΔN_{eff} . Assuming $\Delta N_{\text{eff}} = 1$, we obtained the more stringent bounds $0.5 < \tau_s < 2.5 T_0$ (1σ) and $\tau_s > 0.14 T_0$ (2σ).

Parameters	CMB+SBL	CMB+SBL +LSS+ H_0 +CFHTLenS+PSZ
$\Omega_b h^2$	$0.02273^{+0.00042+0.00086}_{-0.00042-0.00079}$	$0.02267^{+0.00027+0.00056}_{-0.00027-0.00052}$
$\Omega_{\text{cdm}} h^2$	$0.131^{+0.006+0.014}_{-0.007-0.012}$	$0.122^{+0.005+0.013}_{-0.007-0.010}$
θ_s	$1.0397^{+0.0008+0.0017}_{-0.0008-0.0017}$	$1.0406^{+0.0010+0.0017}_{-0.0010-0.0019}$
τ	$0.100^{+0.015+0.032}_{-0.016-0.029}$	$0.083^{+0.013+0.029}_{-0.014-0.027}$
n_s	$0.996^{+0.016+0.034}_{-0.018-0.033}$	$0.991^{+0.010+0.021}_{-0.011-0.019}$
$\log(10^{10} A_s)$	$3.145^{+0.044+0.081}_{-0.043-0.086}$	$3.107^{+0.032+0.064}_{-0.030-0.060}$
r	$0.182^{+0.043+0.099}_{-0.050-0.085}$	$0.206^{+0.042+0.097}_{-0.048-0.086}$
ΔN_{eff}	$1.03^{+0.47+0.97}_{-0.50-0.95}$	$0.66^{+0.33}_{-0.43}, < 1.35$
$m_s [\text{eV}]$	$1.26^{+0.11+0.17}_{-0.16-0.27}$	$1.26^{+0.11+0.17}_{-0.16-0.28}$
$\tau_s [T_0]$	$< 0.13(1\sigma)$	$> 0.22(1\sigma)$
$\Delta\chi^2(\text{A})$	-1.8	-2.1
$\Delta\chi^2(\text{B})$	-8.2	-7.8

TABLE I. Marginalized 1σ and 2σ confidence level limits for the cosmological parameters obtained with the invisible sterile neutrino decays. The decay lifetime τ_s is given in units of the age of the Universe T_0 . $\Delta\chi^2(\text{A})$ and $\Delta\chi^2(\text{B})$ give the variation of the cosmological χ^2 with respect to the fit of cosmological data without (A) and with (B) the SBL prior for the mass of a stable sterile neutrino (corresponding respectively to the grey and red regions and lines in the figures).

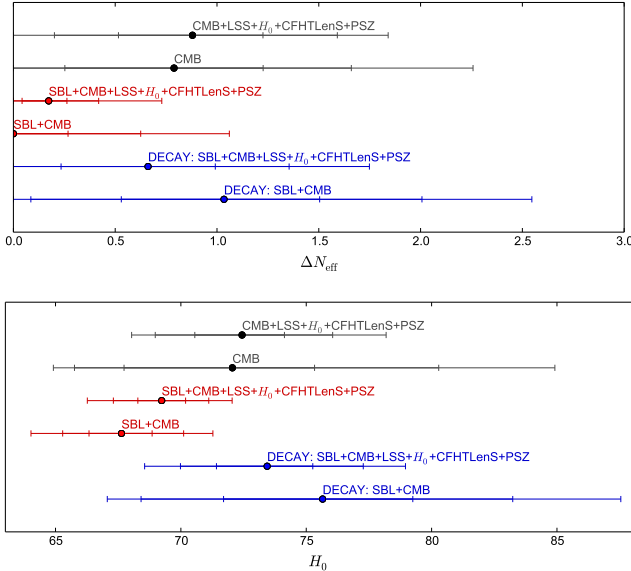


FIG. 2. 1σ , 2σ and 3σ marginalized error bars for ΔN_{eff} and H_0 obtained in the different fits of the cosmological data considered in Figs. 1 and 3. The circles indicate the marginalized best fit value. The black and red intervals are taken from Ref. [5]. The blue intervals are obtained by adding the invisible sterile neutrino decays.

In conclusion, we have proposed to solve the tension between the fit of cosmological data with a sterile neutrino with the mass of about 1 eV indicated by short-baseline neutrino oscillation data and the thermalization of this sterile neutrino in the early Universe by introducing a decay of the sterile neutrino into invisible very light particles. We have shown that a fit of the cosmological data with the SBL prior allows a full thermalization of the sterile neutrino in the early Universe, reconciling the sterile neutrino explanations of oscillations and cosmological data. The decaying massive sterile neutrino has a beneficial effect for the explanation of the observed suppression of small-scale matter density fluctuations and leads to a larger value of the Hubble constant which is in agreement with local measurements.

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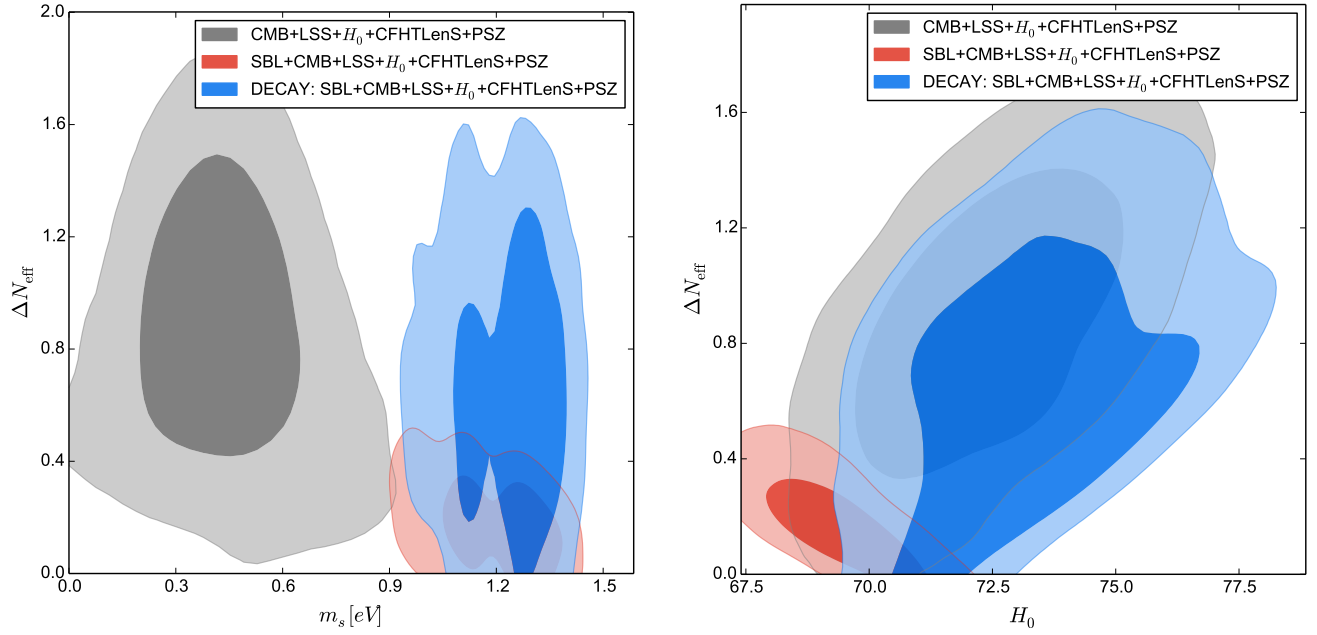


FIG. 3. 1σ and 2σ marginalized allowed regions obtained with the most complete cosmological data set considered in Ref. [5] (the CMB data considered in Fig. 1 plus LSS+ H_0 +CFHTLenS+PSZ). The gray and red regions are those obtained in Ref. [5] without and with the SBL prior. The blue regions are obtained by adding the invisible sterile neutrino decays.

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